RESOURCE QUALITY CASCADES IN TRADITIONAL LOW EXERGY TECHNOLOGIES: THE QANATS AND BADGIRS OF YAZD

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Abstract

Accelerated climate change is manifesting itself in the warming world through increasingly extreme weather events and escalating rates of change. Simultaneously issues of fossil fuel depletion, security of energy supply, population growth, resource depletion, rates of consumption, mounting waste streams and pollution are all potent drivers for radical new resource supply, demand and disposal paradigms. Notions of the optimisation of resource yields and process 'efficiency' dominated 20th century industrial thinking when resource supply was not generally considered a limiting factor. This no longer holds true in the 21st century as demand rises with populations and expectations despite growing physical and economic limits to supply. The systematic exceedance of our eco-system capacities to produce resources and cope with waste informs the growing imperative to 'live within our means', within defined hinterland ecosystems in a symbiotic, non-destructive manner. To do this will require new thinking. This paper attempts to illustrate how traditional resource supply paths, that informed the design of vernacular buildings and settlements, co-evolved with the spatial location of energy and resource demand to produce zero work to waste ratios for particular resource cascades. This point is illustrated by the example of the the *qanats* (water supply systems) and the *badgirs* (building ventilation systems) of Yazd in the Central Desert of Iran. These technologies utilise multi-functional resource quality and exergy cascades to turn homes in the hot, barren Iranian desert into paradise.

1. Introduction

At the SBO8 Conference in Melbourne, Dobbelsteen et al. (2008) outlined new design paradigms based around the concept of 'Smart Vernacular Planning' of buildings and cities, based around the need to optimize the amount of work our societies can do using locally available energy supplies. In order to achieve this new ways of accounting for, exploiting and distributing energy (and other resources) are needed that:

1. Understand and map the qualities and quantities of energy needed to do the required work locally.
2. Map in detail the quality and quantity of locally available energy resources.
3. Design energy and resource systems that theoretically match local energy needs to available supply so as to reduce waste and impacts optimising the work potential of the given system capacity.
4. Devise policy and spatial planning processes to implement such new demand and supply designs.
5. Learn iteratively from the process to continually improve and design new resource flow cascades with a view to ultimately achieving zero work to waste ratios in resource cascades.

In this paper two examples of highly sophisticated traditional water and energy supply systems in Yazd in central Iran demonstrate that the traditional master builders of the region understood, and utilized, optimized resources cascades, to create luxurious living conditions in ostensibly barren deserts. In this extremely arid environment water and coolth are scarce, and yet within the city gardens and rural settlements, levels of luxury can be found that would impress the senses of any world traveller thanks to the extraordinary, highly evolved skills of the resource system designers, the Yazdi *ostads* (master builders) of yore.

Dobbelsteen et al.(2008) pointed out that the 1st and 2nd Laws of Thermodynamics dealing with energy conservation mean that energy, in reality, can neither be created nor destroyed (or consumed or be made more efficient). Energy is rather converted from one form to another on its route to increasing disarray (entropy). As energy degrades so its level of order (exergy) decreases. They point out that designers can, by understanding the characteristics and potential of the resource (energy) at each point along its chain (cascade of states) and by matching that knowledge to the practical need for that resource in the built environment to do particular pieces of work that require the resources in a particular state, then we can maximize the value of that resource as it flows through, and is harnessed in the environment.

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Dobbelsteen et al. (2008) highlighted the 'The low-exergy principle' for the optimal use of energy flows through the built environment. The exergy or quality of energy (reflected in the state of energy degradation of the resource) is used optimally for a series of decreasingly demanding works in processes. Thus high-quality energy is used for high-grade purposes only and low-grade energy, further down the exergy cascade, is used to do less demanding work. This low-exergy principle is already being used in some regions for spatial planning, to produce Heat Maps that map energy sources and couple them with matching spatial demands.

The same principals are widely used in traditional resource supply systems and are most sophisticated where resources are very scarce. This is demonstrated here using the example from settlements in an extremely dry, barren desert in Iran where little or none of the water resource is wasted. The first example of an optimised resource cascade deals with water supplied by a Qanat into the villages of the desert and the second with the coupled energy systems of a badgir or domestic windcatcher in the homes of Yazd. Lessons are drawn from the two examples on how zero work to waste ratios of the resource flows are achieved.

2. The Qanat

2.1 General description of a qanat

A qanat is a gently sloping underground tunnel dug from upland aquifers to provide lowland settlements with water by gravity. It is connected to the surface by a series of vertical shafts used for the construction and repair of the tunnel. Qanats are mainly associated with alluvial fans in piedmont zones and alluvial valleys on desert margins, or with larger inter-montane valleys. Sargon II of Assyria (705-681BC) claimed to have learnt the secret of tapping underground water in his campaign against the Urartians and with the establishment of the Achaemenid Empire the technology spread westwards to the Mediterranean and southwards to Oman and Arabia. A second major spread of qanats took places during the early centuries of Islam (700-1000AD) to Spain and Marakesh and from thence on to Mexico and Chile (Lambton, 1989).

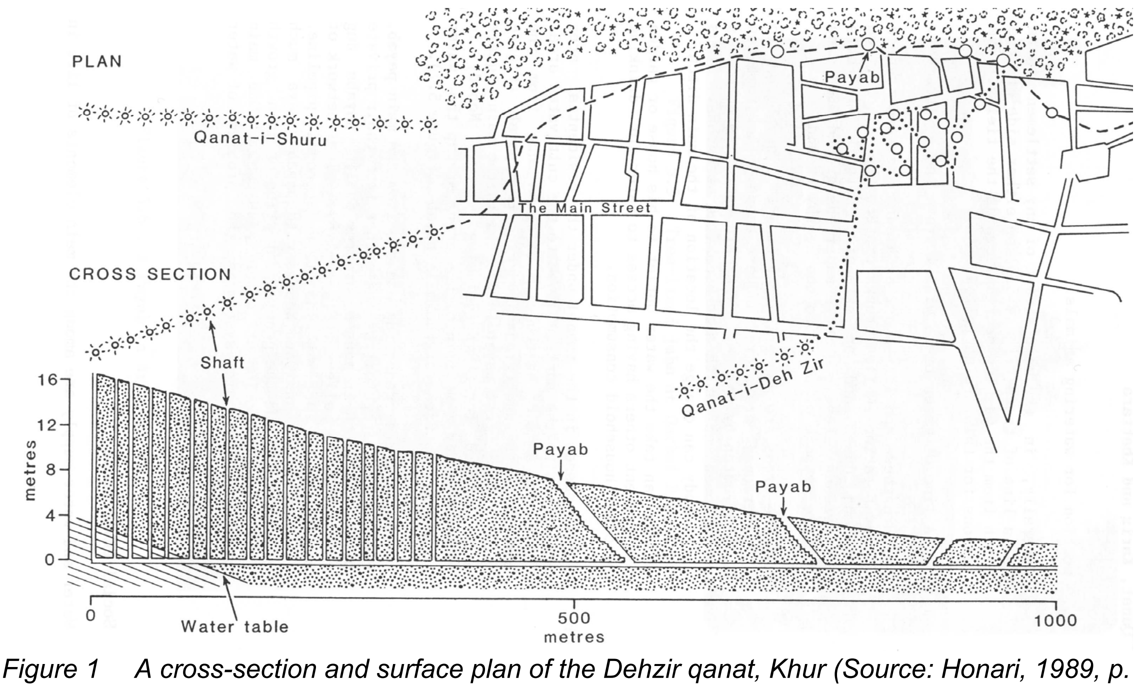

Figure 1 A cross-section and surface plan of the Dehzir qanat, Khur (Source: Honari, 1989, p. 68)

In arid environments surface water supplies are sporadic and unreliable and usually confined to a short season of maximum river discharge. In contrast ground water provides water storage facility that can be tapped at anytime of year. Ground water is most simply harvested with wells but these have the disadvantage that they required energy to raise the water to the surface. In qanats the natural water pressure from the upland aquifers maintain a flow that may vary according to season, the aquifer capacity and water demand. The highest shaft well dug, the mother well, its linked to its settlement by the raha-y qanat, its 'road', and emerges above ground at a *mazhar*, the point where people take water. In many places this may be well below ground level and a set of stairs descend to allow access to the *payab* (foot of the water). The *mazhar* is generally located in the main square, around which a mosque, public baths (*hammam*), water cisterns (*abanbar*), the market (*bazaar)* and a place for water apportioning may also be located. Homes of prominent persons may also be located in this area and some houses are linked to the qanat by their own *payab* stair to the water (Honari, 1989). A complex legal framework and implementation process ensures that very clear and well understood principles and units dictate the amount and times of water supply to the qanat shareholders. The route of the qanat dictates to a significant extent the form of the settlement and its downstream agriculture which is spatially planned to enable and optimise the access to water of different qualities for a range of functions that require different water qualities (Table 1).

2.1 Functions of a qanat in the settlements of the Yazd region

The qanats of Yazd are used to supply water and energy in a sequence functions along their downward path through a settlement. Starting at the top at and after the *mazhar*, by meeting demands for uses that require pure water, then as the water, now flowing not in an underground tunnel but in a surface channel (*jube*), becomes more polluted is used for functions that can manage with dirtier water (table 1 and figure 2). Millennia of refinements have honed the designed of the robust traditional systems for grist milling, cooling buildings, settlements and water (Beazley and Harverson, 1989) and even making and storing ice (Beamon and Roaf, 1990)

Table 1. Descending range of functions of qanat water in an Iranian village with water quality requirements

Structure	Function	water quality required
mazhar	Drinking water collection point	Cold drinking water
abanbar	water cistern	Cold drinking water
yakhtchal	ice house	Cold drinking water
jube	Water channel, pot and cloth washing	bathing water
hamam	bath house	bathing water
asiab	flour mill	c. bathing water
hoz	pond, animal watering	c. bathing water
fields	agriculture	c. bathing water

2.2 Optimising the work to waste ration of the resource cascade

There are numerous ways in which the resource cascade of water and energy quality are manipulated through a village, over a year, ensure that the maximum of work is achieved with a minimum of waste: demand is shaved by shifting loads to be met sequentially within fixed supply profiles for the seasonal flows (demand management – riparian laws); the times of water/energy delivery are shifted by storing it to do targeted work needed later; work is stored until the energy/water is available; the energy potential of the water supply is increased by raising the height, the head, of the water drop across a village in raised canals or mill ponds; the spatial planning of the whole settlement is predicted on the need to physically co-locate water/energy supply and demand requirements (figure 2). Examples of supply and load shaving, shifting and storage methods to optimise work to waste ratios in the system design include:

- Seasonal storage of winter coolth: Drinking water cistern filled when qanat water flow is high and cold in winter and spring and may provide a full years supply stored.
- Climatic determinant in loss minimisation: The hamam water cistern filled in summer by the slower flow during the hot day to avoid evaporative losses and the field watered by the same flow after sunset until dawn so water can sink into the ground and less is lost to evaporation during the heat of the day.
- Seasonal storage of winter coolth. The ice pans of the ice house will be filled with cold winter water for ice production in mid winter when water demand for agriculture is low. Ice is eaten in the hot summer
- Many richer, high water use, families leave the hot settlements for the summer and so reduce demand.
- Domestic water storage is minimal and demand limited by the need to carry or raise the water. Smaller domestic water stores provide warmer drinking water than cooler water from qanats or water cisterns.
- Flour is stored to be milled in the grist mill when adequate flow was available.
- Some villages have a mill pond raising the head of the water making more power available in the mill.
- If insufficient water flowed in a qanat one year grain is taken away to mill, temporarily exporting work.
- Water shortages would be most felt by the animals and the fields.

2. The Badgir

2.1 General description of a badgir

The Badgir, or windcatcher, is a structure that reaches up above the general roof line of a settlement and catches the available wind, channeling it down a shaft into the living rooms below, usually on the ground floor and in the half or full basement. In the different regions of the Middle East windcatchers are built in different forms and sizes dictated to some extent by climatic factors such as diurnal and seasonal temperature ranges and wind speeds, and historical factors (Roaf, 1988). Around Yazd poor agricultural land and lack of water over much of the basin, and the vulnerability of the exposed settlements and caravans, to bandits meant the widespread settlement of the basin was comparatively recent, occurring largely in the late nineteenth and twentieth centuries. Prior to that there were only the two largest cities in the area, Yazd and Nain, and between them several large, well fortified villages such as Haftodor and Aqda, built in Sassanian times (sixth century A.D.) and Bunderabad, built by the Atabegs in the thirteenth century (Bonine, 1980).

The windcatcher types in the Yazd Basin fall into three distinctive groupings: four directional towers around Nain to the north west of the Basin and Yazd to its south east, and one directional towers in the centre of the basin around the towns of Ardakan and Maibud.

A survey of 713 of the badgirs of Yazd city showed that in 1976 over 60% of all windcatchers were less than 3 metres high above roof parapet level and only 15% rise above 5 metres high. This latter group, described in the survey as towers forming recognisable landmarks, numbered about 110 although these numbers are now significantly fewer. The most common type of badgir in the city is a modest structure; around 150 cms high, and typically 120 cms x 100 cms to 200 cms x 100 cms in cross sectional area. There is a 50% probability that it faces in two or four directions, and is in fair condition. It is on the south wall of the house and the larger vents face north west and south east. It has a simple square or round vent head detail. The high towers were built exclusively on larger houses or public buildings indicating that the high badgir probably was a recognised status symbol of wealth and importance to the Yazdi. The high badgirs of Yazd were built in the latter half of the nineteenth century, funded in part by the successful silk trade but to a greater extent by the new found wealth of the Yazdi merchants who dominated the opium supply trade to Iran during the period (Roaf, 2008).

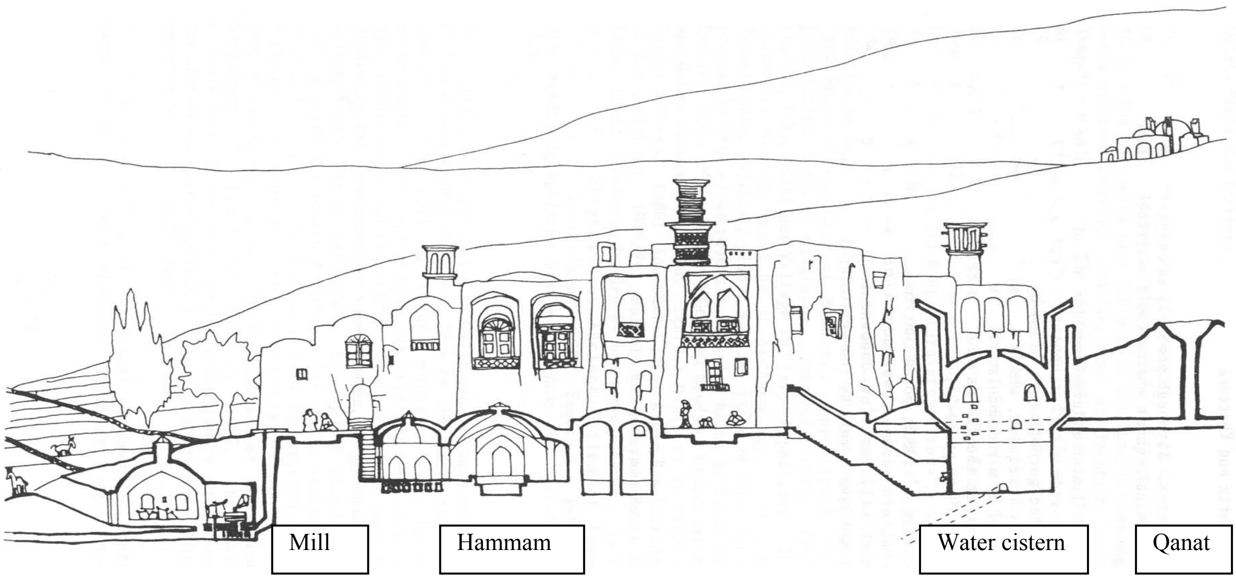

Figure 2 Cross-section of a theoretical village in the Central Iranian Desert showing the path of the qanat water supply and demand base on the village of Kharanaq (Source: Roaf, 1989, p.58).

2.2 How badgirs work

Yazd has a hot, but not very hot (as in Iraq, Saudi or the Gulf States), summer climate with average maximum temperatures in July of 39^{0}C. When the recordings for this study were taken in they showed that on the roof a regular diurnal temperature pattern exists. Typical recorded maximum temperatures in July and August were in the region of 42^{0}C on clear days and 38^{0}C on cooler or overcast days occurring around 2 p.m. - 4 p.m., and minimum temperatures in the region of 26-29^{0}C occurring just before sunrise. Air for the domestic badgirs in Yazd is typically drawn from two areas: from the roof and the courtyard. The courtyard climate is typically higher than roof temperatures during the night keeping benefiting from the radiant warmth of the mud walls but the temperatures in the courtyards will vary considerably according to the dimensions, orientation, vegetation and water features of the court. For instance in the smaller courtyards air temperatures were cooler than in the larger courts during the afternoon from 1 p.m. to 9 p.m., when a greater percentage of the smaller courts were in shade from their own walls. Larger courtyards are cooler at night than smaller ones. It is the very subtle understanding of comfort temperatures and the value of slight temperature differences in the surfaces and air volumes of the buildings and courtyards that enable Yazdi master builders to design comfort into these buildings.

At temperatures between mean skin temperature (32^{0}C), upper mean skin temperature (35^{0}C) and higher the physiological cooling mechanisms are convective and evaporative cooling. Comfort is also achieved using behavioural strategies such as reducing metabolic rates with an afternoon sleep in the heat of the day, wearing of light clothes, moving to the coolest part of the house, watering floors to lower local temperatures, cold and hot drinks, sitting in a draft to increase air movement over the skin and so on. A very detailed knowledge of local wind flow patters and air movement paths through the house is also essential. During the hot summer months Yazd receives a strong prevailing northwest wind. Readings taken of the wind flow in

Yazd over 19 hours suggest that the geographical location of the city on the fringe of the Central Desert strongly influences the diurnal pattern of flow with strong winds from the north west in the mid afternoon, from 5.5 m/sec - 9 m/sec, veering round to the north in the evening and gradually tailing off by the early morning when the wind is negligible. As soon as the land mass begins to heat up, the wind increases in velocity and veers again to the northwest by mid afternoon.

Figure 3 View across the badgirs of the old city of Yazd (source: www.spiritofadventure.com\0.

The tower of the badgir is usually separated into two or more shafts, most commonly four, and this subdivision of the tower allows air to move easily up and down the tower at the same time. When vents face towards and away from the prevailing wind, air is forced, by a build up of pressure on the windward face of the tower and the existence of a lower pressure region at the base of the tower shaft, into the vents and down the tower. The air at the base of the shaft partitions, around 2 to 2.5 metres above ground floor level, issues into the badgir recess from where it may travel into the summer room, down into the basement through a timber grill in the floor, or up the leeward shaft of the tower

In very general terms the four most important functions of the badgirs in Yazdi houses are:

1) Provision of a breeze in summer rooms. During the day badgirs provide summer rooms with a cross draught with speeds averaging typically between 0.3-1.5 m/sec. This increases heat loss from the body largely by convection and evaporation. The reduction in temperature of air moving down the badgir shaft of an average 1^0C - 4^0C between the roof and the ground floor room is important, generally bringing the air temperature to below 37^0C, ie. body temperature, during the hottest time of the day. The exception to this occurs in late afternoon on hot summer days when, in the area directly below the badgir shaft, globe and air temperatures may rise above 37^0C until about 8 p.m. Therefore in early evening a seating position near the open courtyard is usually taken up rather than one beneath the badgir.

2) Reduction of temperatures of walls, floors and ceilings of ground floor summer rooms. Air flow through the ground floor summer rooms at night and during the morning draws heat from the surfaces of the ground floor rooms so lowering the Mean Radiant Temperature of the surfaces of the rooms for 12-14 hours a day, and subsequently decreasing temperatures experienced by occupants of the rooms during the day.

3) Warming the basement. The badgir introduces air into the basement which mixes with the basement air, causing an increase in the air temperature and the Mean Radiant Temperatures, and a decrease in the relative humidity of the space. This heating up of the basement prevents the space from becoming too cold for Yazdi comfort in the afternoon and can enable the basement, if well ventilated, to be used as a sleeping area at night. The increase in basement temperature also reduces the temperature difference between internal and external climate. When moving between the courtyard and the basement climate at noon and in early evening, the occupants experience less contrast in temperature, and therefore less thermal stress.

4) Basement ventilation. The badgir opening into a basement is important for ventilation, particularly for the removal of body, food and smoke odours, and the introduction of oxygen, in a space where 15 people or more may eat and sleep in the afternoon. The reduction of relative humidities, which rise as high as 70% in unventilated basements, by the use of the badgir has implications for the health of the afternoon occupants of the basement. A basement with badgir is said by the Yazdi to reduce respiratory ailments, the incidence of rheumatism and arthritis, although this is perhaps less important than the reduction of the spread of viral and bacterial infection through improved ventilation.

In contrast to the Western approach to design for comfort in which the individual chooses the climate for a room, the Yazdi in a traditional house selects a room for its climate to take advantage of a wide range of thermal and air flow opportunities created by the architecture of the building. While nomads in Iran migrate from summer quarters to winter quarters to avoid the harsh summer climates for those who remain in Yazd replace the long migration by a short intra mural migration, within the walls of a single house. This involves the use of the roof at night, the ground floor in morning and evening, and the use of the basement during the hottest time of the day, between noon and 6 p.m. when maximum levels of direct solar radiation coincide with the highest ambient external temperatures.

2.3 Qanat + Badgir water cooling and air-conditioning systems

The badgir houses of Yazd are operating at the very thresholds of 'acceptable' climate. In areas with an average maximum monthly temperature of 2^{0}C higher than that of Yazd, such physiologically acceptable temperature thresholds may be exceeded, and particularly easily where a large badgir is used in a ground floor summer room. However the Yazdi ostad has one final trick up his sleeve. He steals the coolth of the mountain stream, born a thousand meters above the city from the earth of 'Lion Mountain' and introduces it into his basements using the two thousand year old technology of the qanat. In the fine old houses of the bazaar quarter of Yazd, many of the lower basements have a flight of steps down from the courtyard to the payab, the level of the water. Well shafts are built to the qanat water from the kitchens and through these water is drawn up via winding wheels. Also well shafts are sunk from the summer afternoon living room basements into the qanat water channels to introduce cool humid mountain air into the basement.

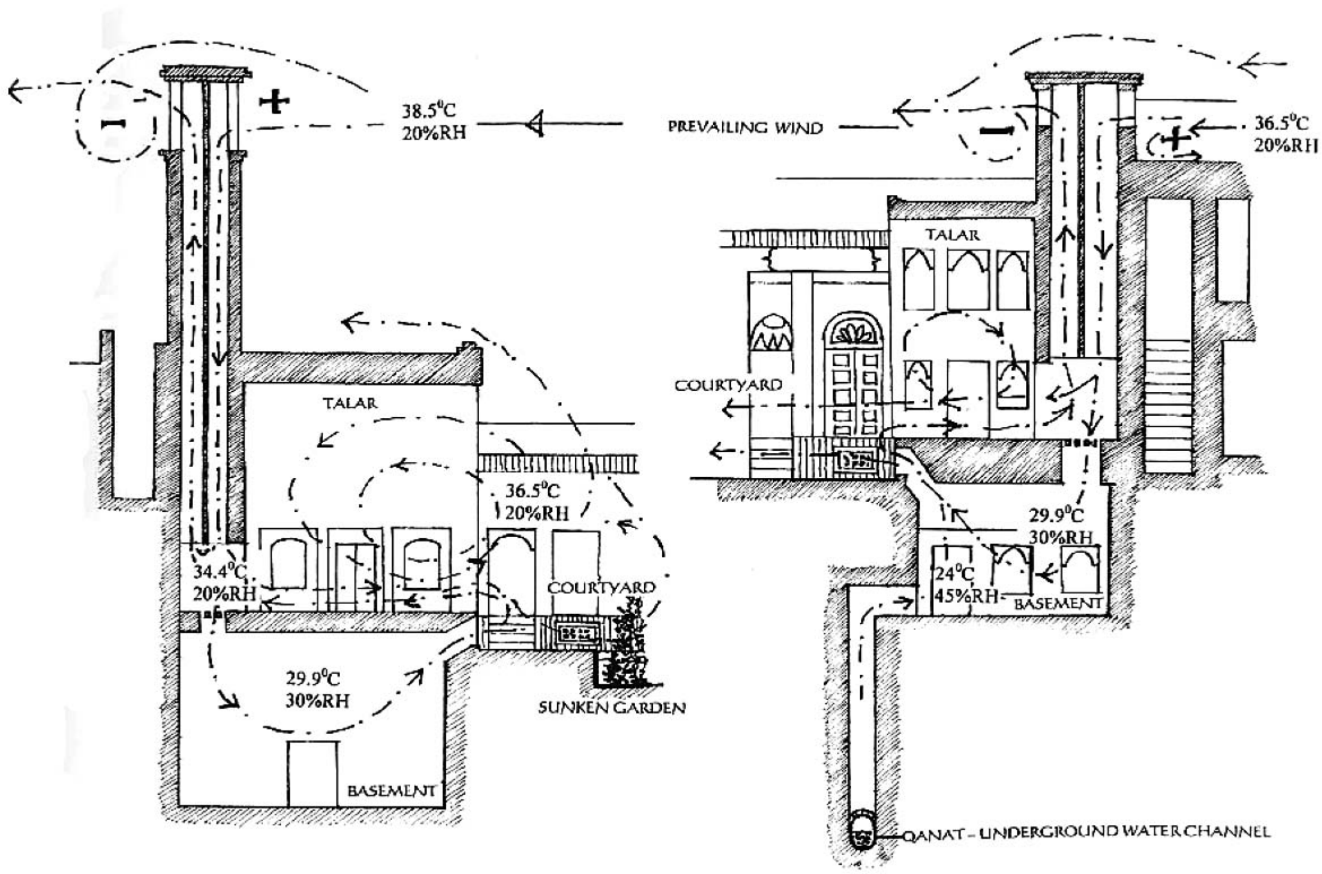

Figure 4 Section through two basements with badgirs of which one is linked to the payab, the water level of the qanat by a vertical well so introducing mountain coolth into the summer afternoon living areas of the basement (Source: Roaf, 1988).

Qanats range in length from 300 meters to 65 kilometers and in many the slope of fall is very gentle to reduce pressure on the tunnel walls that may damage them. In one tunnel of the Korde-Sofla Two qanat in the Najafabad valley, the 1.216klm long tunnel falls only 26 cms over its distance and the temperature within it varies in temperature from 10^0C to 13.5^0C over the year with very little difference between the temperature of the water at the mother well and the point it emerges from the ground (Hartle, 1989).

Figure 4 show the reduction in the basement temperature of nearly 5^0C of introducing the cool mountain air into it via the qanat tunnel linked to the mountains and the shaft that links the basement and the water level.

Figure 5 shows the extraordinary configuration of the qanat, badgir and basement at the Bagh-e Khan garden in Taft half way between Yazd and the mountains. Here the owner had the idea to build the 14m high badgir some 50 meters away from the garden pavilion in the middle of the fruit trees of the garden. The underground tunnel linking tower with the basement passes over the qanat tunnel taking the cool air directly

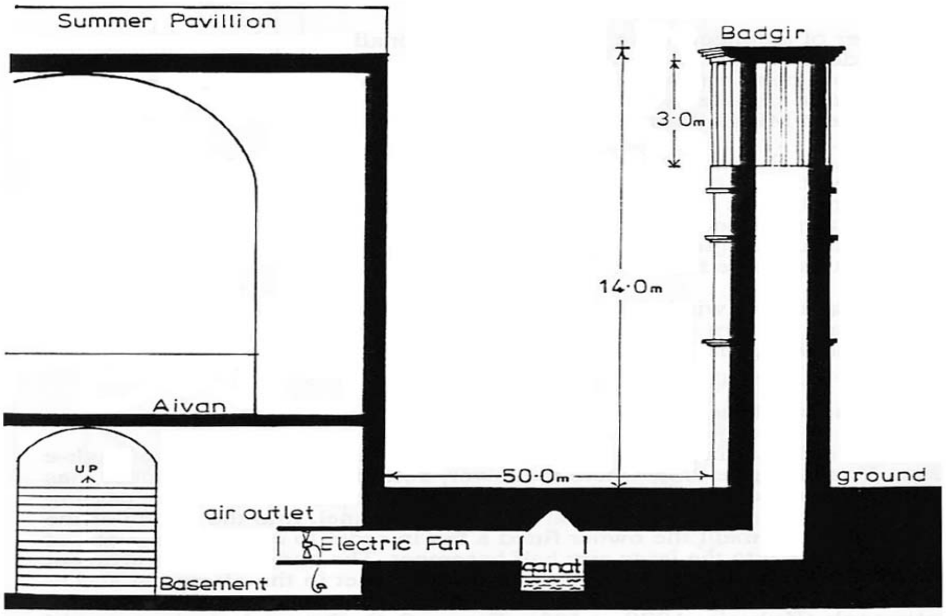

Figure 5. Section through the badger, qanat and basement of the Bagh-e Khan pavilion (source: Sue Roaf)

to the basement. Because of the distance, and the surface resistance of the tower tunnel he found that the air flow rates into the basement were poor so he added a small electric fan in the mouth of the tunnel and was then able to boast, and be admired as, the man with the best air conditioning system in Yazd. He placed his bed near the tower tunnel outlet.

A further method of generating coolth is by incorporating one to six wind towers around the circumference of the water cistern so that the air passing across the water surface will evaporative cool the stored water, but of course the more that evaporate the more is lost to use. It is common to have water temperature from the payab level from which the water is drawn near the base of the water cistern to be 20^0C cooler than air temperature at street level (Figure 2).

4. Conclusions

In the qanat, and the combination of the qanat and the badger, we have an example of two highly sophisticated water and energy supply technologies that do much of the work required to enable at times luxurious lifestyles to be hewn from the barren desert floor. These technologies do this by using elegant resource quality and energy cascades that rely on a profound understanding of low exergy design principals to not only do the work but also to virtually remove waste from the system altogether.

Mother Well – gravity fed spring

Bagh-e Khan – basement cooling - qanat + badgir

Water cistern – cold water storage - qanat + bagir

Ice house – freezing and storing water - qanat

Mazhar - Cold drinking water - qanat

House Basements – air-conditioning – qanat + badger

Jube - Bathing / washing – qanat

Mill - Grist milling – qanat

Drinking pond for animals – qanat

Fields – agriculture – qanat

WASTE = ZERO

The traditional technologies of the Central Desert of Iran have perhaps the most sophisticated building, water and energy systems in the world. They have been systematically evolved over millennia, spurred on by the overwhelming necessity of optimising the value of the extremely scare resources, and informed by the inter-generational wisdom, skills and ingenuity of the master builders of the region. These systems have enabled comfortable lifestyles to be created in a hot climatic region using no use of fossil fuels at all but rather dependent on systems driven with the clean renewable resources of water, wind and air.

To achieve this requires not only the hardware of the technologies but also:

- The intertwining of the vertical and horizontal spatial planning to take advantage of proximity, gravity and sequential co-location of functions
- Energy storage in building, ice and water masses
- Supply and demand management and regulation with load shifting, shaving, reduction and shedding
- Life style adaptation to take maximum advantage of resources, including heat and coolth, when they become available
- Four dimensional system planning with a deep understanding of the relationship between resource, climate, ecosystem and time.

The result is a total human ecosystem that co-exists in harmony with the nature that supports it, produces zero waste and a hundred years ago would have left almost no impact on the face of the earth when it melted back into the mud from whence it came. How ironic that we in our uber-developed societies should have to turn to the wisdom of such apparently simple builders to re-learn the lessons of creating zero waste to work life support systems.

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